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Ultraviolet photodetectors fabricated from ZnO *p–i–n* homojunction structures

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ABSTRACT

Zinc oxide (ZnO) *p–i–n* structured ultraviolet (UV) photodetector has been constructed in this paper. The photodetector exhibits an obvious response to ultraviolet light at 0 V bias, which is a typical character of *p–i–n* structured photodetectors. The maximum responsivity of the photodetector, which is located at around 390 nm, is about 0.45 mA W^{-1} at 0 V bias, and the responsivity increases with increasing reverse bias voltage applied. The response decay time of the *p–i–n* structured photodetector is about 260 ns. This is the first report on ZnO *p–i–n* homojunction structured photodetectors to the best of our knowledge. Considering that *p–i–n* structure is the most promising configuration for high performance photodetectors, the results reported in this paper may provide a clue for high-performance ZnO based UV photodetectors.

1. Introduction

Ultraviolet (UV) photodetectors have drawn much interest in recent years due to their versatile potential applications in missile detection, space-to-space communication, flame detection and combustion monitoring, etc. [1–3]. As an important wide band gap semiconductor, zinc oxide (ZnO) exhibits excellent photosensitive properties at UV spectrum region, while it is almost transparent at visible region [4–6]. The above characters make ZnO an ideal candidate for UV photodetectors. Actually, ZnO based photodetectors have been studied extensively in recent years, and various typed ZnO photodetectors have been demonstrated, such as metal–semiconductor–metal [7–10], schottky [11–13], *p–n* junction [14–17], photoconductive type [9,18,19], etc. It is accepted that *p–i–n* junction structured photodetectors have a variety of figure of merits such as high breakdown voltage, fast response, low dark current compare with other structured ones. However, since the obtaining of reliable and reproducible *p*-type ZnO is still a challenge [20–23], none report on *p–i–n* homojunction structured ZnO photodetectors can be found to the best of our knowledge. Recently, on the basis of realizing high quality ZnO films with low residual electron concentration [24,25], we have obtained reproducible *p*-type ZnO by employing lithium-nitrogen as dual-acceptor dopants [25], which lays a solid ground for the realization of *p–i–n* structured ZnO photodetectors.

In this paper, *p–i–n* homojunction structured ZnO photodetectors have been fabricated. A noticeable responsivity at around 390 nm was observed from the photodetector, and the maximum responsivity of the photodetector is about 0.45 mA W^{-1} at 0 V bias, which increases with increasing the reverse bias applied.

2. Experimental

The growth of the ZnO films was carried out in a VG V80H plasma-assisted molecular beam epitaxy technique, and the detailed growth conditions can be found elsewhere [25]. Briefly, metallic zinc (99.9999%), metallic lithium (99.999%) and oxygen gas (99.9999%) and nitric oxide gas (99.9999%) were employed as the precursors and dopants for the growth. Knudsen cells were used to evaporate metallic sources, and Oxford Applied Research radio-frequency (13.56 MHz) atomic cells (Model HD25) operating at 320 W were used to activate gassy sources. The *p*-type lithium-nitrogen doped ZnO (ZnO:(Li,N)) layer was grown at 750 °C, the insulating active layer (*i*-ZnO) of the *p–i–n* structure was grown at 800 °C, and the *n*-type ZnO layer was grown at 750 °C. The electrical properties of the ZnO films were measured in a Hall measurement system (LakeShore 7707) under Van der Pauw configuration. The photoresponse of the *p–i–n* junction photodetector was measured using a standard lock-in amplifier, a Spex scanning monochromator, and a 150 W Xe lamp was employed as the irradiation source. The transient response of the ZnO *p–i–n* photodetector was measured under the excitation of the 266 nm line of a Nd:YAG

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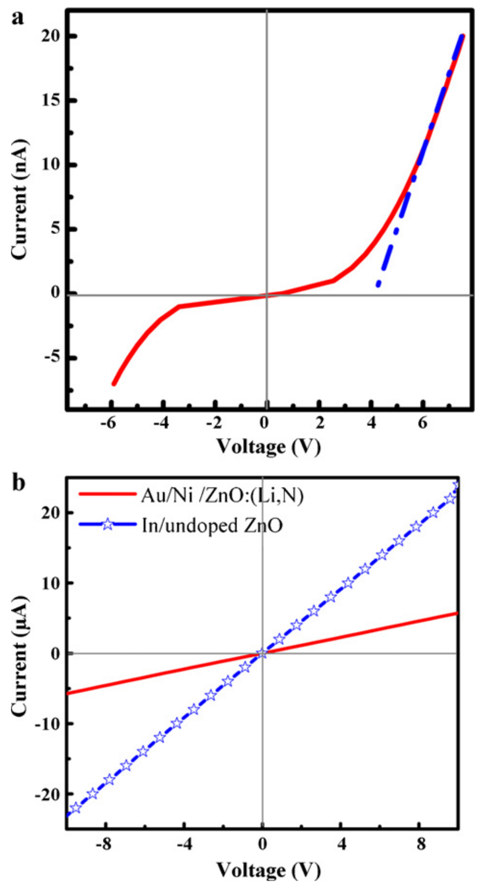

Fig. 1. (a) *I–V* curve of the ZnO:(Li,N)/undoped-ZnO junction, indicating obvious rectifying behaviors with a turn-on voltage of about 4.2 V; and (b) *I–V* cures of Ni/Au contact on the ZnO:(Li,N) layer and In contact on the undoped ZnO layer, showing both of them are good ohmic contacts.

laser with the pulse width of 10 ns, and the transient signals were recorded by a Triax 550 spectrograph.

3. Results and discussion

Hall measurement on the ZnO:(Li,N) film indicates that the film is of *p*-type conduction, and the hole concentration and mobility are 4.5×10^{16} cm^{-3} and 8.7 cm^2 V^{-1} s^{-1}, respectively. To further identify the conductivity type of the ZnO:(Li,N) films, the doped ZnO films were deposited on an undoped *n*-ZnO layer. The *I–V* curve of the ZnO:(Li,N)/*n*-ZnO structure is shown in Fig. 1(a). A perceptible rectifying behavior can be observed from the *I–V* curve, and the turn-on voltage of the structure is about 4.2 V. Note that both the *I–V* curves of the Ni/Au contact on the ZnO:(Li,N) layer and In contact on the *n*-ZnO layer are typical beelines, as shown in Fig. 1(b), revealing that good ohmic contacts have been obtained on both layers. The above facts indicate that the rectifying behaviors observed in the *I–V* curve of the ZnO:(Li,N)/*n*-ZnO structure comes from the ZnO:(Li,N)/undoped n-ZnO interface, and confirming the Hall result that the ZnO:(Li,N) is of *p*-type conduction.

A schematic illustration of the *p–i–n* structured photodetector is depicted in Fig. 2(a). The device is consisted of three epitaxial layers: *n*-ZnO, *i*-ZnO, and *p*-type ZnO:(Li,N). The thickness of the *n*-ZnO is 300 nm, and the electron concentration and mobility of the layer are 4.3×10^{19} cm^{-3} and 31.0 cm^2 V^{-1} s^{-1}, respectively. The *i*-ZnO layer has an electron concentration of 1.5×10^{16} cm^{-3}, and the mobility of this layer is 28 cm^2 V^{-1} s^{-1}. The hole concentration and mobility of the *p*-ZnO:(Li,N) film are 4.5×10^{16} cm^{-3} and 8.7 cm^2 V^{-1} s^{-1}, respectively. The growth details of *i*-ZnO and *p*-

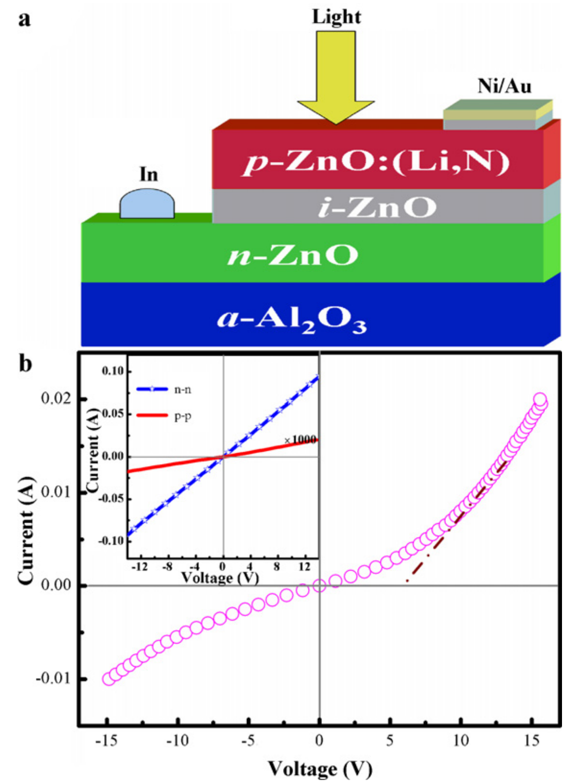

Fig. 2. (a) Schematic illustration of the ZnO *p–i–n* structured photodiode; and (b) *I–V* curve of the *p–i–n* structure, and the inset shows the *I–V* curves of the the Ni/Au contact on *p*-ZnO:(Li,N) layer and In contact on *n*-type ZnO layer.

ZnO:(Li,N) can be seen in our previous report [25]. Ni/Au and In were deposited using vacuum evaporation as *p*-type and *n*-type contacts, respectively. In this way, a ZnO based *p–i–n* photodetector has been constructed. The *I–V* curve of the *p–i–n* structure is shown in Fig. 2(b). From the *I–V* curve, well-defined rectifying behaviors can be observed, and the turn-on voltage is about 6.0 V. Note that the large turn-on voltage may be caused by the relatively high resistance of the *i*-ZnO layer. The Ni/Au electrode on the *p*-type ZnO layer and the In electrode on the *n*-type ZnO layer are both good ohmic contacts, as revealed by the straight lines shown in the inset of Fig. 2(b).

The photoresponse characteristics of the *p–i–n* structured photodetector are shown in Fig. 3. It is found that a noticeable response has been observed at 0 V bias. The maximum responsivity of the

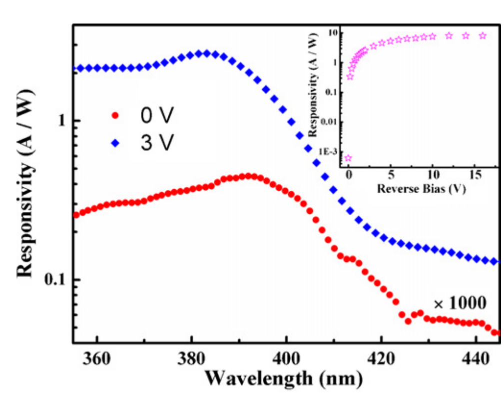

Fig. 3. Photoresponse of the ZnO *p–i–n* homojunction photodetector at 0 V and 3 V reverse bias (note that the responsivity of 0 V has been magnified by 1000 times), and the inset shows the responsivity at 390 nm of the structure as a function of the reverse bias applied.

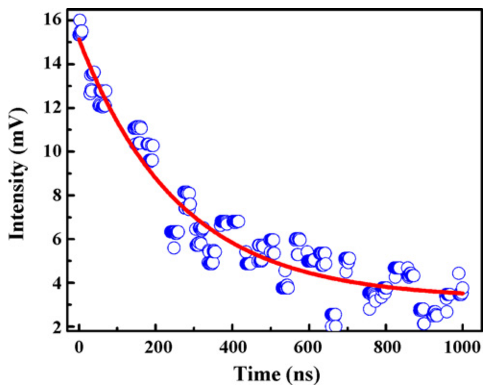

Fig. 4. Photoresponse decay of the *p–i–n* structured ZnO UV photodetector, in which the scattered circles are experimental data, while the solid line is a fitting to the experimental data using a first-order exponential decay formula.

photodetector is about 0.45 mA W^{-1} located at around 390 nm, which corresponds to the band gap of ZnO, and the cutoff wavelength is located at around 405 nm. The obvious photoresponse at 0 V bias is a typical character of *p–i–n* structured photodetectors, confirming that the photoresponse comes from the *p–i–n* homojunction. The peak responsivity at around 390 nm of the structure as a function of the reverse bias applied is shown in the inset of Fig. 3. The responsivity of the photodetector increases with increasing reverse bias, and it can reach about 8 A W^{-1} at 12 V bias. It is noted that although there are some reports on ZnO *p–n* ultraviolet photodetectors [14–17], no report on ZnO *p–i–n* homojunction structured photodetectors can be found before to the best of our knowledge.

The temporal response decay spectrum of the ZnO *p–i–n* structured photodetector is shown in Fig. 4. The spectrum was measured with a load resistor of 7.5 kΩ at 0 V bias. The scattered experimental data can be well fitted by the following first-order exponential decay formula:

$$I = I_0 + A_0^* \exp\left(\frac{-t}{\tau}\right) \quad (1)$$

where I and I_0 are the response of the photodetector, τ is the decay lifetime, t is time, and A_0 is a constant. The best fitting of the experimental data using Eq. (1) yields a decay time of 260 ns for our *p–i–n* structured photodetector. That is, the response decay time of the *p–i–n* structured photodetector is about 260 ns.

4. Conclusion

In summary, *p–i–n* structured ZnO UV photodetector has been fabricated in this paper. The photodetector shows obvious response of about 0.45 mA W^{-1} to UV light at 0 V bias, which is a typical character of *p–i–n* structured photodetectors. The maximum responsivity of the photodetector can reach 8 A W^{-1} when the reverse bias reaches 12 V. This is the first report on *p–i–n* structured ZnO photodetectors to the best of our knowledge. Considering that *p–i–n* structured photodetector has significant figure of merit compare with other structured ones, such as MSM, schottky, photoconductive type. The results reported in this paper demonstrated a route to *p–i–n* homojunction structured photodetectors, thus may provide a clue for realizing high performance ZnO-based UV photodetectors in the future.

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